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Electric Vehicle – Wireless Charging-Discharging Lane Decentralized Peer-to-Peer Energy Trading

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ABSTRACT This paper investigates the problem of bidirectional energy exchange between electric vehicles (EVs) and road lanes embedded with wireless power transfer technologies called wireless charging-discharging lanes (WCDLs). As such, EVs could provide better services to the grid, especially for balancing the energy supply-demand, while bringing convenience for EV users, because no cables and EV stops are needed. To enable this EV–WCDL energy exchange, a novel decentralized peer-to-peer (P2P) trading mechanism is proposed, in which EVs directly negotiate with a WCDL to reach consensus on the energy price and amounts to be traded. Those energy price and amounts are solutions of an optimization problem aiming at optimizing private cost functions of EVs and WCDL. The negotiation process between EVs and WCDL is secured by a privacy-preserving consensus protocol. Further, to assure successful trading with desired energy price and amounts, an analytical and systematic method is proposed to select cost function parameters by EVs and WCDL in a decentralized manner. Simulations are then carried out to validate the developed theoretical results, which confirm the effectiveness and scalability of the proposed algorithm.

INDEX TERMS Electric vehicle, wireless power transfer, wireless charging discharging lane, peer-to-peer energy trading, privacy-preserving consensus.

NOMENCLATURE

DR	Demand response.
EV	Electric vehicle.
IWPT	Inductive wireless power transfer.
MAS	Multi-agent system.
P2P	Peer-to-peer.
WCDL	Wireless charging-discharging lane.
WPT	Wireless power transfer.
$E_{V,i}$, $E_{L,i}$, E_L	Trading energy of EV i, of WCDL with EV i, and total trading energy of WCDL [kWh].
$f_{V,i}$, f_L	Private cost functions of EV i and WCDL.
$a_{V,i}$, $b_{V,i}$	Parameters in the cost function of EV i.
a_L, b_L	Parameters in the cost function of WCDL.
$\underline{E}_{V,i}$, $\overline{E}_{V,i}$	Lower and upper bounds for trading energy of EV i.
$\underline{E}_L$, $\overline{E}_L$	Lower and upper bounds for trading energy of WCDL.

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I. INTRODUCTION

Recent disasters worldwide as aftermaths of global climate changes, which greatly affect to human living and global economics, urge serious actions from every country, in which reducing greenhouse gas (GHG) emissions is a must. To achieve that, transportation and energy systems should be on priority, since their portions in the total GHG emissions are highest among industrial sectors.

Currently, transportation systems are increasingly being electrified, while energy systems including electric power grids are witnessing a rapid transformation from fossil fuel based and centralized generation to renewable based and distributed generation. Nevertheless, massive deployment of EVs faces great challenges due to: (i) high cost; (ii) limited range due to limited efficiency and capacity of energy conversion and storage devices, e.g., battery or fuel cell; and (iii) limited number of charging points. Similarly, current energy infrastructure and markets are not ready for a prompt transition to sole renewable generation and decentralized operations.

Wireless power transfer (WPT) has recently emerged as a promising approach to overcome the aforementioned drawbacks of EVs deployment [1]–[6]. Especially, the concept of dynamic wireless charging, enabled through wireless charging lanes, help extend traveling ranges of EVs, while giving convenience to EV owners, since no stops and cables are required for charging EVs. Therefore, dynamic wireless charging creates a mutual relation between transportation and energy systems, in which EV serves as a bridge. To further faciliate that mutual relation, this research investigates the bidirectional WPT between EVs and the so-called WCDLs, i.e., EVs are able to not only get charging from WCDLs but also discharge to WCDLs.

The EV–WCDL bidirectional energy exchange is attractive due to its capability of on-the-fly charging and discharging – a great option that brings the ultra-mobility and availability to energy, as well as convenience and comfort for users. Furthermore, EV fleets can serve as a super-flexible and clean resource for providing a wider range of ancillary services to the grid. In areas with deep penetration of renewables, e.g., California, USA, or Kyushu, Japan, curtailments on renewable power generation were made to guarantee the energy supply-demand balance, even with some types of energy storage systems [7]. In such situations, charging or discharging from a large number of EVs could help reduce the curtailed amount and diminish the so-called duck curve [7], where ancillary services can be provided by EV fleets not only at noon when they are parked at homes or offices but also in the morning and in the afternoon when they are moving on roads. As a result, both transportation and energy systems can become low-carbon emission systems.

From the energy system perspective, a WCDL supplemented with renewable sources (e.g., solar, wind, etc.) along roadsides (see e.g., Figure 1) can be regarded as a prosumer who can both produce and consume energy. Likewise, an EV with on-site storage systems (e.g., battery, supercapacitor, etc.) can also be regarded as a prosumer. Thus, energy exchange between an EV group and a WCDL is in fact energy trading between prosumers, of which innovative market models have recently been studied, for instance the so-called P2P energy market. A number of works in the recent literature has been devoted to investigate P2P energy systems, see e.g., [8] and references therein. Accordingly, different approaches have been proposed as P2P energy trading mechanisms. For example, game theory was used in [9]–[14], bilateral contracts were investigated in [15]–[18], multi-class energy management was introduced in [19]. Next, continuous double auction was presented in [20], supply-demand ratio based pricing was utilized in [21], mixed performance indexes were considered in [22], federated P2P energy systems were proposed in [23].

However, in all of those works, the problems of how to select parameters of prosumers' cost functions and how to tune them if the derived energy transactions are unsuccessful or unsatisfied have not been investigated. Recently, a heuristic approach for multi-seller-multi-buyer P2P energy systems has been introduced in [24], which has been shown effective in several decentralized P2P energy trading systems [24], [25], but no analytical approach for such systems has existed so far. Another recent paper [26] considered P2P energy sharing between EVs and a business entity, e.g., commercial building with on-site solar power generation, while the trading was made with the utility. Nevertheless, an operator was needed to supervise the P2P energy sharing, i.e., the scheme is distributed, and a simple rule-based control algorithm was used in [26].

To the author's best knowledge, this research is the first to study the P2P bidirectional energy trading between EVs and WCDLs. The main contribution of this research is a novel P2P energy trading strategy between multiple EVs and a WCDL, with details explained in the following.

- The trading peers negotiate for a range of desired energy price, instead of trying to reach a single price value, at the beginning of the trading process.
- A decentralized and analytical method to select parameters in the cost functions of EVs and WCDL to achieve successful P2P energy transactions with energy amounts in their expected ranges. This selection method also ensures the clearing P2P energy price belongs to the negotiated energy price interval. This analytical method has not been reported in the literature hitherto (including our recent works [24], [25]).

Moreover, the negotiation between multiple EVs and a WCDL for P2P energy trading is conducted through a secure consensus algorithm, where a privacy-preserving mechanism is employed to avoid exposing private parameters of EVs and the WCDL.

Note, however, that a decentralized and analytical method to tune cost function parameters of prosumers in P2P energy markets having multiple sellers and multiple buyers cannot be straightforwardly derived from the current paper's result. Thus, further investigations are needed to derive analytical methods for tuning prosumer cost function parameters in multi-seller-multi-buyer P2P energy trading systems.

The rest of this paper is organized as follows. In Section II, system description is given, and problems are formulated. Consequently, a decentralized P2P energy trading mechanism for EVs and the tuning of cost function parameters for the WCDL and EVs are proposed in Section III. The illustrating simulations are presented in Section V. Lastly, the paper is summarized and future research direction is given in Section VI.

II. SYSTEM DESCRIPTION

A. WIRELESS CHARGING-DISCHARGING LANE

In this research, it is assumed that the resonant IWPT technology is used for the WCDL, where coils are placed under the WCDL and under the chassis or in the wheels of EVs (see e.g., [5], for WPT between wireless charging lanes and EVs with in-wheel motors and coils). The WCDL and considered IWPT technology are illustrated in Figure 1.

Denote the number of underground wireless power transceivers by n_c, and the length of each charging-discharging segment in the WCDL (assumed the same length

FIGURE 1. Illustration for EVs charged/discharged by wireless charging-discharging lanes with renewables along roadsides (upper), and under-road wireless charging-discharging segments (lower). (Photos are adopted with modifications from https://www.magment.de/de-dynamic-wireless-charging, and https://en.reset.org/blog/turning-roads-smart-charging-solutions-electric-cars-07052018).

for all segments) by ℓ_c. When the ith EV is charged from the WCDL, the energy it receives is calculated by

$$E_{c,i} = P_r \eta_{d,r} \eta_{c,i} n_i \frac{\ell_c}{v_{wpt}}, \tag{1}$$

where $E_{c,i}$ is the received energy by EV i; P_r is the rated power of each transmitting segment; $\eta_{d,r}$ is the wireless discharging efficiency of the segments; $\eta_{c,i}$ is the charging efficiency of EV i; n_i $(\leq n_c)$ is the number of charging-discharging segments that the ith EV passes through; and v_{wpt} is the designated velocity on the WCDL. A similar formula can be derived when the ith EV is discharged to the WCDL as follows,

$$E_{d,i} = P_{EV,i} \eta_{d,i} \eta_{c,r} n_i \frac{\ell_c}{v_{wpt}}, \tag{2}$$

where $E_{d,i}$, $P_{EV,i}$, $\eta_{d,i}$ are the discharged energy, discharged power, and wireless discharging efficiency, of EV i, respectively; $\eta_{c,r}$ is the wireless charging efficiency of the segments.

Note that the number of charging/discharging segments n_i that an EV will pass by depends on the amount of energy agreed to trade by such EV and the WCDL.

B. ISSUES ON WIRELESS ENERGY EXCHANGE FOR EVs

In order for enabling P2P energy exchange between EVs and WCDLs, a P2P market clearing mechanism, which is the main issue, needs to be derived. This P2P energy trading can also be regarded as a mechanism to incentivize EV owners for actively participating in demand response (DR) programs. Hence, a novel approach will be proposed in Section III to address it. The negotiation between EVs and a WCDL is supported by a proper information and communication infrastructure, assumed readily available.

An additional issue arises on the coordination of multiple EVs, e.g., when they switch between normal lanes and WCDLs. This problem can be suitably dealt with by platoon formation control methods which have been extensively investigated in the literature as a solution to improve the smoothness of traffic flows and energy saving for the whole vehicle group. A well-established framework to study formation control problems is multi-agent system (MAS) (see e.g., [27]–[31]), where each vehicle is cast as an agent. It should be noted that for vehicle formation control, the inter-vehicle information such as relative position and relative speed are most essential. Therefore, the edge (i.e., the vehicle-to-vehicle or agent-to-agent) dynamical evolution is very important. Recently, several works [32]–[39] have studied MASs using edge dynamics, by which the formation control problems are converted to equivalent stabilization problems at the origin which is much easier to deal with than the consensus problems on manifolds. But none of the works in [32]–[38] considered the formation control problems of vehicles under the changes on speeds of vehicles and on road lanes. The problems of both model uncertainty and exogenous inputs in the formation control of autonomous EVs have been coped with in our recent studies [40], [41]. However, to make the current paper focused, details on the formation control of EVs will not be presented.

III. EV–WCDL DECENTRALIZED PRIVACY-PRESERVING OPTIMAL TRADING

In this section, a bidirectional trading mechanism between EV and WCDL prosumers is proposed. As mentioned in Section II-B, the P2P energy trading between EVs and WCDL owners can be considered as an incentive mechanism for EV owners to join in DR programs. This is especially useful to flatten steep ramps (up and down) on the net load curve, which could occur around noon and in the evening when renewable outputs are very high and very low, respectively. Therefore, WCDL owners do not set fixed energy price, but instead let EV owners negotiate the energy trading price and amount to encourage them charge or discharge in advance of their plans. It is worth emphasizing that the charging/discharging of EVs through WCDLs considered in this paper does not mean to completely replace the conventional charging/discharging of parked EVs (at homes, offices, etc.), but instead an alternative solution to it.

There would be multiple WCDLs and many EVs that could exchange energy with the others, however, different from stationay prosumers such as households with rooftop solar panels, EVs are mobile prosumers. Therefore, EV owners would choose the closest WCDL (to their routes) for energy trading, i.e., each EV sells or buys energy to only one WCDL. Hence, in the following, we formulate and solve the P2P energy trading between n EVs and one WCDL.

A. CHARACTERIZATION OF OPTIMAL SOLUTION

Each EV prosumer (EV owner) has an objective function, assumed to be quadratic and convex, see e.g., [15], [16], [21], [24], [25]), as follows,

$$f_{V,i}(E_{V,i}) = a_{V,i}E_{V,i}^2 + b_{V,i}E_{V,i}, \tag{3}$$

where $a_{V,i} > 0$ and $b_{V,i} > 0$ are constant coefficients known only by EV prosumer i, $E_{V,i}$ is the traded energy of EV i. Likewise, a WCDL prosumer (WCDL owner) has a cost function, also assumed to be quadratic and convex (see e.g., [15], [16], [21], [24], [25]),

$$f_L(E_L) = a_L E_L^2 + b_L E_L, \tag{4}$$

where $a_L > 0$ and $b_L > 0$ are constant coefficients known only by the WCDL prosumer, E_L is the traded energy of the WCDL. Thus, the optimization to be solved for the P2P energy trading between EVs and a WCDL is

$$\min \sum_{i=1}^{n} f_{V,i}(E_{V,i}) + f_L(E_L) \tag{5a}$$

$$\text{s.t. } E_{V,i} + E_{L,i} = 0, \tag{5b}$$

$$\underline{E}_L \le E_L = \sum_{i=1}^{n} E_{L,i} \le \overline{E}_L, \tag{5c}$$

$$\underline{E}_{V,i} \le E_{V,i} \le \overline{E}_{V,i}. \tag{5d}$$

When EVs are charged by the WCDL, $E_{V,i} > 0$, $E_{L,i} < 0$, hence $\underline{E}_{V,i} = 0$, $\bar{E}_L = 0$. Likewise, as EVs are discharged to the WCDL, $E_{V,i} < 0$, $E_{L,i} > 0$, and $\bar{E}_{V,i} = 0$, $\underline{E}_L = 0$. For conciseness, in the following only the scenario of EV charging is presented, and the case of EV discharging can be obtained in a similar manner.

The optimization problem for EV-WCDL P2P energy trading, when EVs are charged, is as follows.

$$\min \sum_{i=1}^{n} f_{V,i}(E_{V,i}) + f_L(E_L) \tag{6a}$$

$$\text{s.t. } E_{V,i} + E_{L,i} = 0, \tag{6b}$$

$$\underline{E}_L \le E_L = \sum_{i=1}^{n} E_{L,i} \le 0, \tag{6c}$$

$$0 \le E_{V,i} \le \bar{E}_{V,i}. \tag{6d}$$

The Lagrangian associated with (6) is

$$\begin{aligned}\mathcal{L} = & \sum_{i=1}^{n} f_{V,i}(E_{V,i}) + f_L(E_L) - \sum_{i=1}^{n} \lambda_i (E_{V,i} + E_{L,i}) \\ & - \mu_{L,1}(E_L - \underline{E}_L) + \mu_{L,2}E_L \\ & - \sum_{i=1}^{n} \hat{\mu}_{V,i}E_{V,i} + \sum_{i=1}^{n} \check{\mu}_{V,i}(E_{V,i} - \bar{E}_{V,i}),\end{aligned}$$

where λ_i, $\mu_{L,1} \ge 0$, $\mu_{L,2} \ge 0$, $\hat{\mu}_{V,i} \ge 0$, $\check{\mu}_{V,i} \ge 0$ are Lagrange multipliers associated with the constraints (6b)–(6d). Next, the following assumptions are employed.

A1: Successful trading for the WCDL and all EVs.

A2: The constraints (6c) and (6d) are strictly feasible.

Remark 1: The above assumptions are temporarily employed here to simplify the characterization of optimal solutions of (6). Later, in Section IV, a method will be introduced to guarantee successful trading between EVs and the WCDL, and to strictly satisfy the constraints (6c)–(6d), i.e., to satisfy both assumptions **A1** and **A2**.

Because the cost functions of EVs and the WCDL are assumed as in (3) and (4) and all constraints are linear, the mathematical programming (6) is convex. Therefore, KKT conditions are necessary and sufficient for (6), which read as follows,

$$\left.\frac{\partial f_{V,i}(E_{V,i})}{\partial E_{V,i}}\right|_{E_{V,i}^*} - \lambda_i - \hat{\mu}_{V,i} + \check{\mu}_{V,i} = 0, \tag{7a}$$

$$\left.\frac{\partial f_L(E_L)}{\partial E_{L,i}}\right|_{E_{L,i}^*} - \lambda_i - \mu_{L,1} + \mu_{L,2} = 0, \tag{7b}$$

$$E_{V,i}^* + E_{L,i}^* = 0, \tag{7c}$$

$$\mu_{L,1}\left(\sum_{i=1}^{n} E_{L,i}^* - \underline{E}_L\right) = 0, \quad \mu_{L,2}E_{L,i}^* = 0,$$

$$\hat{\mu}_{V,i}E_{V,i}^* = 0, \quad \check{\mu}_{V,i}(E_{V,i}^* - \bar{E}_{V,i}) = 0, \tag{7d}$$

where $E_{V,i}^*$ and $E_{L,i}^*$ are optimal values of $E_{V,i}$ and $E_{L,i}$, respectively. Then, assumption **A1** leads to $\hat{\mu}_{V,i} = 0$ and $\mu_{L,2} = 0$, while assumption **A2** implies that $\check{\mu}_{V,i} = 0$ and $\mu_{L,1} = 0$. Thus, (7) becomes

$$2a_{V,i}E_{V,i}^* + b_{V,i} - \lambda_i = 0, \tag{8a}$$

$$2a_L \sum_{i=1}^{n} E_{L,i}^* + b_L - \lambda_i = 0, \tag{8b}$$

$$E_{V,i}^* + E_{L,i}^* = 0. \tag{8c}$$

Equation (8b) reveals that all the energy prices λ_i for individual P2P trading between the WCDL and one EV are the same. Denote this unique price by λ. Next, dividing both sides of (8a) by $a_{V,i}$, both sides of (8b) by a_L, summing them up and utilizing (8c), we obtain

$$0 = \sum_{i=1}^{n} \frac{b_{V,i}}{a_{V,i}} + \frac{b_L}{a_L} - \lambda \left(\sum_{i=1}^{n} \frac{1}{a_{V,i}} + \frac{1}{a_L}\right),$$

$$\Leftrightarrow \lambda = \left(\sum_{i=1}^{n} \frac{b_{V,i}}{a_{V,i}} + \frac{b_L}{a_L}\right) \Big/ \left(\sum_{i=1}^{n} \frac{1}{a_{V,i}} + \frac{1}{a_L}\right). \tag{9}$$

Accordingly, the optimal energy to be traded by the WCDL and each EV are as follows,

$$\sum_{i=1}^{n} E_{L,i}^* = E_L^* = \frac{1}{2a_L}(\lambda - b_L),$$

$$E_{V,i}^* = \frac{1}{2a_{V,i}}(\lambda - b_{V,i}). \tag{10}$$

B. DECENTRALIZED PRIVACY-PRESERVING NEGOTIATION OF P2P MARKET CLEARING PRICE

It is obvious from (9) that the P2P market clearing price between the WCDL and EVs is calculated using information from all of them. Nevertheless, each EV is only communicated with the WCDL for energy trading, hence a mechanism to attain (9) in a decentralized manner is needed. This is achievable by using consensus algorithms for MASs, such as the following.

Let the WCDL and EVs run a consensus algorithm with variables x_0 (for the WCDL) and x_i (for EV i), whose initial values are set to be:

$$x_0(0) = \left[\frac{b_L}{a_L}, \frac{1}{a_L}\right]^T,$$
$$x_i(0) = \left[\frac{b_{V,i}}{a_{V,i}}, \frac{1}{a_{V,i}}\right]^T, \quad i = 1, \ldots, n. \tag{11}$$

At time step $k \geq 0$, the WCDL and each EV communicate to run the following consensus algorithm,

$$x_i(k+1) = a_{ii}x_i(k) + \sum_{j \in \mathcal{N}_i} a_{ij}x_j(k), \quad i = 0, 1, \ldots, n, \tag{12}$$

where $0 < a_{ij} < 1 \ \forall j \in \mathcal{N}_i$, $0 < a_{ii} < 1$ are constant parameters satisfying $\sum_{j=0}^{n} a_{ij} = 1 \ \forall i = 0, \ldots, n$, and $\mathcal{N}_i$ denotes the set of peers communicated with peer i. There are multiple ways to choose a_{ij}, e.g. the Metropolis weights [42], or that in [43]. Then it can be proved (see [42], [43]) that all variables x_i reach the average consensus vector $x_{ave} = [x_{ave,1}, x_{ave,2}]^T$, as $k \to \infty$, where

$$x_{ave,1} \triangleq \frac{\sum_{i=1}^{n} \frac{b_{V,i}}{a_{V,i}} + \frac{b_L}{a_L}}{n+1}, \quad x_{ave,2} \triangleq \frac{\sum_{i=1}^{n} \frac{1}{a_{V,i}} + \frac{1}{a_L}}{n+1}. \tag{13}$$

As such, the P2P market clearing price λ is computed by the WCDL and each EV as follows,

$$\lambda = \frac{x_{ave,1}}{x_{ave,2}}. \tag{14}$$

As seen from (12), the initial values of the WCDL and EVs are exchanged, therefore their private parameters a_L, b_L and $a_{V,i}, b_{V,i}$ are exposed, which is a critical privacy issue that they do not want. To clear this concern, several approaches can be employed to secure the WCDL-EV information exchange, which can be categorized into encrypted and non-encrypted approaches. For the former, Paillier additive homomorphic cryptosystem is currently one of the most used algorithms for public key cryptography (see e.g., [44]). For the latter, a few studies have been conducted to obtain secure consensus algorithms that converge exactly to the average of agents' initial values (see e.g., [45]). While the former can provide better privacy guarantee, its computational complexity is higher, hence induces longer computational time. Thus, there is always a tradeoff between privacy and computation overhead for secure consensus algorithms.

It is worth emphasizing that *decentralized cryptosystem* is still a hard problem. For example, the work in [44] required an assumption that each agent has at least a trustable neighboring agent who does not try to infer the other agent's initial condition. On the other hand, the masking approach in [45] necessitated the non-overlapping neighboring sets between agents, therefore in star networks, such as that in the current research, can only guarantee the privacy of the center node (the WCDL in the current research), but cannot protect the privacy of the other nodes (EVs in the current research). To this end, derivation of a decentralized privacy-preserving algorithm for consensus problem, which is applicable to any network topology and uses non-conservative assumptions, needs much more works, hence should be considered in a separated study.

For the current research, if we assume that the WCDL owner has a limited computability that prevents it from trying to infer private parameters of many EVs communicated to it for P2P energy trading, i.e., initial values of EVs in (11), then the masking approach in [45] can be utilized. This is stated in the following proposition.

Proposition 1: Each peer (whether the WCDL or an EV) sets its initial value as in (11), and creates a masked state

$$\tilde{x}_i(k) = x_i(k) + [w_{i,1}(k), w_{i,2}(k)]^T, \tag{15}$$

in which $w_{i,1}(k)$ and $w_{i,2}(k)$ are random noises generated by:

$$w_{i,\ell}(k) = \begin{cases} \zeta_{i,\ell}(0), & \textit{if } k = 0, \\ \alpha_i^k \zeta_{i,\ell}(k) - \alpha_i^{k-1}\zeta_{i,\ell}(k-1), & \textit{otherwise}, \end{cases} \tag{16}$$

for $\ell = 1, 2$, where $\zeta_{i,\ell}(k)$ are Gaussian random variables independently generated by each peer i from a standard normal distribution, i.e., a normal distribution with mean 0 and variance 1; and $0 < \alpha_i < 1$ are constants. Consequently, each peer runs the following secure algorithm,

$$x_i(k+1) = a_{ii}\tilde{x}_i(k) + \sum_{j \in \mathcal{N}_i} a_{ij}\tilde{x}_i(k), \quad i = 0, 1, \ldots, n, \tag{17}$$

where a_{ij} are the same with that in (12). Then the average consensus is asymptotically achieved for all peers, i.e., $\lim_{k \to \infty} x_i(k) = x_{ave}$, with x_{ave} specified in (13).

Proof: It was proved in [45] the privacy-preserving consensus algorithm (17) converges exactly to the average vector x_{ave} shown in (13), therefore the proof is omitted here for brevity. ■

Note that α_i are distinct for $i = 0, 1, \ldots, n$, hence the generation of noises $w_i(k)$ is completely independent (fully decentralized) for the considering peers.

IV. SELECTION OF COST FUNCTION PARAMETERS FOR DESIRED EV–WCDL P2P ENERGY TRADING

As seen in Section III, the P2P energy trading between the WCDL and EVs strongly depends on their cost functions, more specifically their cost function parameters a_L, b_L, and $a_{V,i}, b_{V,i}$. Nevertheless, how to analytically set the values of those parameters for deriving expected energy transaction price and energy amounts is *ad hoc* for the WCDL and each EV owner, and has not been addressed in the literature. Therefore, in this section a cooperative strategy is proposed to tune cost function parameters of the WCDL and EVs for attaining desired energy transactions, based on the analytical solution (9)–(10) of the P2P optimal clearing problem (6).

A. DECENTRALIZED SETTING OF COST FUNCTION PARAMETERS

Since $E_L^* < 0$ and $E_{V,i}^* > 0 \ \forall\ i = 1, \ldots, n$, it is obtained from (10) that

$$b_{V,i}^{\max} < \lambda < b_L, \tag{18}$$

where $b_{V,i}^{\max} \triangleq \max_{i=1,\ldots,n} b_{V,i}$. Therefore, the WCDL and EVs need to set their parameters b_L and $b_{V,i}$ properly to obtain a desired energy trading price. Here, it is proposed that each EV and the WCDL selects its range of expected trading price, denoted by $[\underline{\lambda}_i, \overline{\lambda}_i], i = 0, 1, \ldots, n$, where the subscript 0 represents the WCDL. Consequently, these price ranges will be exchanged between EVs and the WCDL to obtain a common range of price for all. This cooperative negotiation procedure follows standard consensus algorithms similarly to that in (12), where lower and upper bounds of EV and WCDL prices are updated by such consensus algorithms, as follows,

$$\underline{\lambda}_i(k+1) = a_{ii}\underline{\lambda}_i(k) + \sum_{j\in\mathcal{N}_i} a_{ij}\underline{\lambda}_i(k),$$
$$\overline{\lambda}_i(k+1) = a_{ii}\overline{\lambda}_i(k) + \sum_{j\in\mathcal{N}_i} a_{ij}\overline{\lambda}_i(k), \tag{19}$$

for $i = 0, 1, \ldots, n$, where $a_{ij}, i, j = 0, \ldots, n$ are the same with that in (12). Note that no secure algorithm is needed here because each EV and the WCDL need to know exactly the price range of the other.

After reaching consensus on the price range, denoted by $[\underline{\lambda}, \overline{\lambda}]$, EVs and WCDL need to set their parameters to assure successful and expected P2P energy transactions. To do so, EVs and WCDL choose their parameters as in the following theorem.

Theorem 1: Having the consensus price range $[\underline{\lambda}, \overline{\lambda}]$, the lower bound $\underline{E}_L$ of WCDL desired selling energy amount, and the upper bounds $\overline{E}_{V,i}$ of EVs' desired buying energy amounts, the following conditions are sufficient for strictly guaranteeing the constraints (6c)–(6d),

$$b_{V,i} \in \left[\underline{\lambda}, \frac{1}{2}(\underline{\lambda}+\overline{\lambda})\right), \ b_L \in \left(\frac{1}{2}(\underline{\lambda}+\overline{\lambda}), \overline{\lambda}\right], \tag{20a}$$

$$a_{V,i} \le \frac{\overline{\lambda}-\underline{\lambda}}{2\overline{E}_{V,i}}, \tag{20b}$$

$$\frac{\overline{\lambda}-\underline{\lambda}}{2}\left(\frac{-1}{\underline{E}_L} - \frac{1}{\sum_{i=1}^n \overline{E}_{V,i}}\right) < a_L < \frac{b_L - \frac{\overline{\lambda}+\underline{\lambda}}{2}}{\sum_{i=1}^n \overline{E}_{V,i}}. \tag{20c}$$

Proof: It is obvious from (20a) that this selection ensures $b_{V,i}^{\max} < b_L$ and $\lambda \in [\underline{\lambda}, \overline{\lambda}]$. It can also be easily shown that $\lambda < b_L$ by utilizing (9). Next, to guarantee that $b_{V,i}^{\max} < \lambda$, we substitute $\lambda - b_{V,i}^{\max}$ into (9) to obtain the following condition,

$$0 < \sum_{i=1}^n \frac{b_{V,i} - b_{V,i}^{\max}}{a_{V,i}} + \frac{b_L - b_{V,i}^{\max}}{a_L},$$

which is true if

$$0 < \sum_{i=1}^n \frac{b_{V,i}^{\min} - b_{V,i}^{\max}}{a_{V,i}} + \frac{b_L - b_{V,i}^{\max}}{a_L}$$
$$\Leftrightarrow (b_{V,i}^{\max} - b_{V,i}^{\min}) \sum_{i=1}^n \frac{1}{a_{V,i}} < \frac{b_L - b_{V,i}^{\max}}{a_L}, \tag{21}$$

where $b_{V,i}^{\min} \triangleq \min_{i=1,\ldots,n} b_{V,i}$. Due to (20a), we further obtain the following condition as a sufficiency for (21), hence for (18),

$$\frac{\overline{\lambda}-\underline{\lambda}}{2} \sum_{i=1}^n \frac{1}{a_{V,i}} < \frac{1}{a_L}\left(b_L - \frac{\overline{\lambda}+\underline{\lambda}}{2}\right). \tag{22}$$

Next, let $[\underline{E}_L, 0)$ and $(0, \overline{E}_{V,i}]$ be the ranges of desired energy amounts to be traded for the WCDL and EV i, as in (6c) and (6d). Utilizing (10) and (18), we obtain

$$E_{V,i}^* < \frac{1}{2a_{V,i}}\left(b_L - b_{V,i}\right) \le \frac{1}{2a_{V,i}}\left(b_L - b_{V,i}^{\min}\right). \tag{23}$$

Note that $b_L \le \overline{\lambda}$ and $b_{V,i}^{\min} \ge \underline{\lambda}$, therefore a sufficient condition for attaining $E_{V,i}^* < \overline{E}_{V,i}$ is that

$$\frac{1}{2a_{V,i}}\left(\overline{\lambda}-\underline{\lambda}\right) \le \overline{E}_{V,i} \ \Leftrightarrow\ \frac{1}{2a_{V,i}} \le \frac{\overline{E}_{V,i}}{\overline{\lambda}-\underline{\lambda}}, \tag{24}$$

which is equivalent to (20b). Moreover, this gives EVs a way to choose their parameters $a_{V,i}$ in a completely decentralized manner.

Now, substituting (20b) into (22) results in the following condition for a_L such that (22) is satisfied,

$$\sum_{i=1}^n \overline{E}_{V,i} < \frac{1}{a_L}\left(b_L - \frac{\overline{\lambda}+\underline{\lambda}}{2}\right) \ \Leftrightarrow\ a_L < \frac{b_L - \frac{\overline{\lambda}+\underline{\lambda}}{2}}{\sum_{i=1}^n \overline{E}_{V,i}}. \tag{25}$$

On the other hand, the following should be satisfied for the WCDL,

$$\underline{E}_L < E_L^* = \frac{\lambda - b_L}{2a_L} = \frac{1}{2a_L}\frac{\sum_{i=1}^n \frac{b_{V,i}-b_L}{a_{V,i}}}{\sum_{i=1}^n \frac{1}{a_{V,i}} + \frac{1}{a_L}}. \tag{26}$$

We have $b_{V,i} - b_L \ge b_{V,i}^{\min} - b_L \ge \underline{\lambda} - \overline{\lambda}$, hence the following condition is sufficient for (26),

$$(\underline{\lambda}-\overline{\lambda})\frac{\frac{1}{2a_L}\sum_{i=1}^n \frac{1}{a_{V,i}}}{\frac{1}{\sum_{i=1}^n a_{V,i}} + \frac{1}{a_L}} > \underline{E}_L$$
$$\Leftrightarrow 2a_L + \frac{2}{\sum_{i=1}^n \frac{1}{a_{V,i}}} > \frac{\underline{\lambda}-\overline{\lambda}}{\underline{E}_L}. \tag{27}$$

Using (20b), the following is sufficient for (27),

$$2a_L + \frac{\overline{\lambda} - \underline{\lambda}}{\sum_{i=1}^{n} \overline{E}_{V,i}} > \frac{\underline{\lambda} - \overline{\lambda}}{\underline{E}_L}$$
$$\Leftrightarrow a_L > \frac{\overline{\lambda} - \underline{\lambda}}{2} \left(\frac{-1}{\underline{E}_L} - \frac{1}{\sum_{i=1}^{n} \overline{E}_{V,i}} \right). \quad (28)$$

Combining (25) and (28) leads to (20c). ■

Remark 2: Note that the range for a_L specified in (25) and (28) requires the upper bounds $\overline{E}_{V,i}$ of traded energy from EVs, which are sent to the WCDL as a part of negotiation procedure. Furthermore, using (25) instead of (22), though results in a stricter condition, helps protect the privacy of EVs since their private parameters $a_{V,i}$ will not be sent to the WCDL.

Remark 3: Result of Theorem 1 implies that with proper selections of cost function parameters, EVs and WCDL can attain successful P2P energy trading with desired energy price and amounts, and without Assumptions **A1–A2**. This result is novel, and has not been obtained hitherto in the literature.

Remark 4: Although presented results in the current paper are derived for the specific problem of EV–WCDL P2P energy trading, they are applicable to other problems having similar problem settings. Particularly, the result of Theorem 1 is true for any system with star network structure.

B. SUMMARY OF THE PROPOSED P2P ENERGY TRADING MECHANISM

Denote *max_iter* the maximum number of iterations for the consensus algorithms (12), (17), and (19). Let ϵ be a given small positive number. The proposed decentralized P2P energy trading mechanism between the WCDL and EVs is summarized in Algorithm 1.

Remark 5: The appealing point of the proposed approach in Algorithm 1 is that no iterative process is needed for solving the arising optimization problem in the P2P energy trading, or for heuristically tuning the prosumer cost function parameters. Therefore, much computational effort can be saved.

However, Algorithm 1 is derived only for one-seller-many-buyer and one-buyer-many-seller contexts, and is not applicable for many-seller-many-buyer cases. Thus, further works should be conducted for the latter general scenarios. It is anticipated that in many-seller-many-buyer scenarios, the number of iterations for the consensus negotiations would be smaller than that in the current paper, due to the smaller value of the second-largest eigenvalue of the Laplacian matrix of the network graph. Nevertheless, the number of decision variables per EV will also be significantly increased, which would make the overall negotiation procedure more slowly.

Algorithm 1 Decentralized P2P Energy Trading for Charging EVs From the WCDL

WCDL and EVs choose their initial price ranges;
EVs select maximum energy amounts $\overline{E}_{V,i}$ to be charged through the WCDL, and send them to the WCDL;
WCDL chooses its upper bound $\underline{E}_L$ of energy amount to trade with EVs;
% Negotiation of energy trading price range;
for $1 \le k \le$ *max_iter* **do**
  WCDL and EVs run the consensus algorithm (19);
  if $k =$ *max_iter*, or $|\underline{\lambda}_i(k+1) - \underline{\lambda}_i(k)| \le \epsilon$, $|\overline{\lambda}_i(k+1) - \overline{\lambda}_i(k)| \le \epsilon \; \forall\, i = 0, \ldots, n$, **then**
    break;
  end if
end for
WCDL and EVs obtain the common P2P energy trading price range $[\underline{\lambda}, \overline{\lambda}]$;
% Selection of cost function parameters
WCDL and EVs select b_L and $b_{V,i}$ to satisfy (20a);
EVs choose $a_{V,i}$ to satisfy (20b);
WCDL selects a_L to satisfy (20c);
% Privacy-preserving negotiation of P2P energy trading price
for $1 \le k \le$ *max_iter* **do**
  WCDL and EVs run the masked consensus algorithm (17);
  if $k =$ *max_iter*, or $\|\tilde{x}_i(k+1) - \tilde{x}_i(k)\|_2 \le \epsilon \; \forall\, i = 0, \ldots, n$, **then**
    break;
  end if
end for
WCDL and EVs compute the P2P energy trading price λ by (14);
WCDL and EVs compute the P2P energy trading amount by (10);

V. NUMERICAL SIMULATION

This section aims at demonstrating the proposed P2P energy trading algorithm between the WCDL and EVs. Assume that the rated power by the WCDL is 400 kW, the resonant IWPT efficiency is $\eta_{d,r} = 90\%$, the conversion efficiency of the electronic circuit on EVs is $\eta_{c,i} = 95\%$, the total length of wireless charging segments is 3 km, and the speed of EVs on the WCL is $v_{wpt} = 50$ km/h (which is the limit on most urban roads in Japan), then the maximum energy that one EV can get from the WCDL, computed in (1), is 20.52 kWh. Here, the number of EVs is first assumed to be 50.

As shown in Algorithm 1, the WCDL and EVs first set their initial price range for the negotiation. It is noted that the feed-in tariff (FIT) in Japan for the fiscal year 2020 is 21 JPY/kWh for solar generation units with capacity under 10 kW [46]. Therefore, it is assumed here that the WCDL initially set its price range to be [24, 28] JPY/kWh to incentivize EVs, whereas EVs expect a higher price with their initial lower and upper bounds of price ranges randomly selected around 27 JPY/kWh and 31 JPY/kWh. Then, utilizing the consensus algorithm (19), the negotiation between WCDL and EVs is depicted in Figure 2. It is obtained that $\underline{\lambda} = 27.2$ JPY/kWh, and $\overline{\lambda} = 31.04$ JPY/kWh.

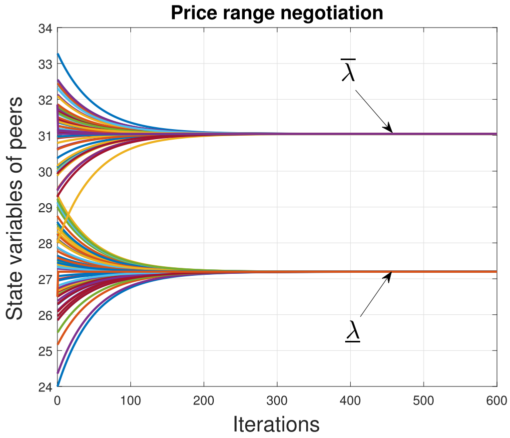

FIGURE 2. Negotiation of P2P energy price between the WCDL and EVs.

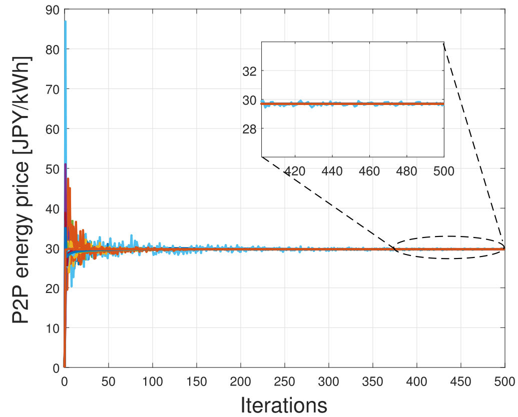

FIGURE 4. Privacy-preserving P2P trading energy price along the negotiation.

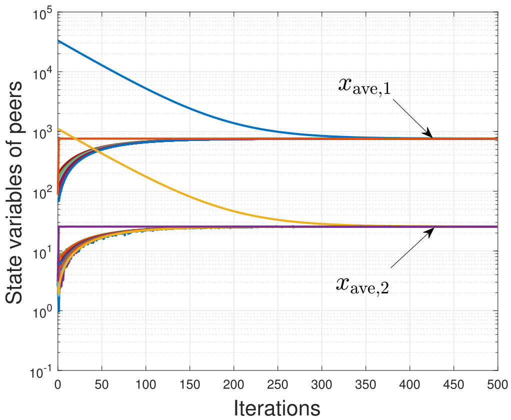

FIGURE 3. Privacy-preserving consensus of peers.

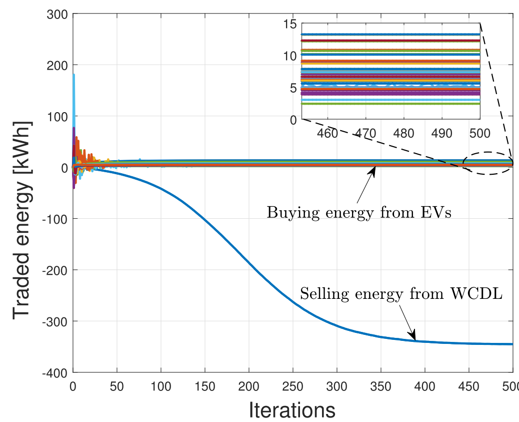

FIGURE 5. P2P traded energy of WCDL and EVs.

Next, EVs set their maximum amounts of traded energy $\overline{E}_{V,i} = 15$kWh, and send to the WCDL. Then the WCDL set $\underline{E}_L = -700$kWh. Consequently, following (20a), WCDL choose its b_L to be 30, while EVs randomly select their $b_{V,i}$ between 27.2 and 29.12. In the next step, EVs randomly choose their parameters $a_{V,i}$ such that they satisfy (20b), which in this case reads $a_{V,i} \geq 0.128$. For the WCDL, condition (28) is always satisfied here, because the right hand side is negative. On the other hand, condition (25) says $a_L < 0.0012$, hence it is chosen to be 0.0009. Afterward, WCDL and EVs run the masked consensus algorithm (17) to derive the P2P market clearing price λ, whose results are shown in Figure 3–5. It can be observed that even in the presence of added noises, state variables of WCDL and EVs still converge to their averages, and hence, their ratio, i.e., the P2P market clearing price converge exactly to the optimal solution (9), as depicted in Figure 4. Moreover, all EVs are successfully traded with the WCDL, as exhibited in Figure 5.

Finally, the scalability of the proposed P2P energy trading algorithm is tested, where the number of EVs is increased from 50 to 100, 150, and 200. It is noted that all the results presented in Section III and Section IV are analytical, hence the running time of the proposed decentralized P2P energy trading algorithm for EVs and WCDL depends on that of the consensus protocols and communication time between EVs and WCDL. Here, the latter is ignored, and only the former is checked, whose results are plotted in Figure 6. It can be observed that the running time is increased almost linearly with system size, thus the proposed algorithm is scalable well.

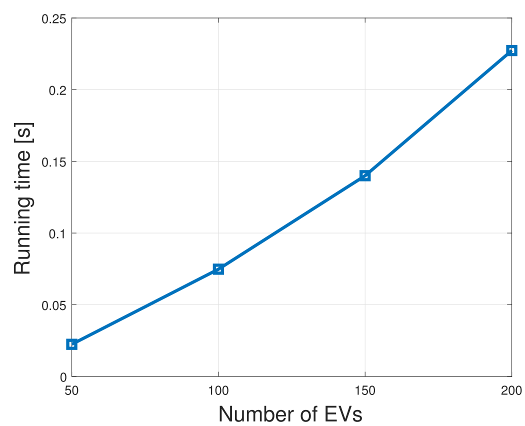

FIGURE 6. Running time of the proposed EV–WCDL P2P energy trading algorithm (without communication time between EVs and WCDL).

VI. CONCLUSION

A decentralized P2P energy trading algorithm has been proposed in this paper for energy exchange between EVs and a WCDL. Analytical formulas for the P2P market clearing price and optimal energy trading amounts have been obtained, based on which a decentralized method has been introduced to properly select the cost function parameters of both the EVs and the WCDL such that all peers successfully trade with desired energy price and energy amounts. It is remarkable that this method is analytical, hence no iterative procedure is needed to tune such parameters. Further, a privacy-preserving approach has been employed to protect peers from private information leak. The proposed algorithm performance and scalability are well verified through a test case.

In the future work, decentralized and analytical methods should be developed for tuning cost function parameters of prosumers in P2P energy markets having multiple buyers and multiple sellers, since the method in the current paper is only for the scenarios of single-buyer-multiple-sellers and single-seller-multiple-buyers. In such systems, the convergence of the whole negotiation procedures should be compared with that in the current work to show the impact of different network structures.

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